DOE/NOAA/OTEC-29

PRELIMINARY DESIGN FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) STATIONKEEPING SUBSYSTEM (SKSS)

TASK IV. Development and Testing Recommendations

MASTER

November 9, 1979

Work Performed Under Contract No. EG-77-A-29-1078

Lockheed Missiles & Space Company, Inc.
Ocean Systems
Sunnyvale, California

U.S. Department of Energy

Solar Energy

DISCLAIMER

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TASK IV - DEVELOPMENT AND TESTING RECOMMENDATIONS

LMSC-D677783 9 November 1979

Prepared for

National Oceanographic and Atmospheric Administration

Office of Ocean Engineering

Prepared by

Ocean Systems Lockheed Missiles & Space Company, Inc.

With

IMODCO

Simplex Wire and Cable Company

Eager and Associates

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FOREWORD

Lockheed Ocean Systems is performing the Preliminary Design for OTEC Stationkeeping Subsystems (SKSS) study contract NA-79-SAC-00635 for NOAA, Office of Ocean Engineering, in support of the Department of Energy, Ocean Thermal Energy Conversion (OTEC) program. The SKSS design team includes IMODCO on design and analysis of mooring systems for the spar (Section 3), Simplex Wire and Cable Company on SKSS interface with the Electrical Transmission System riser cable, and Eager & Associates on reliability assessment. The results of Task IV Development and Testing Recommendations are presented in this report.

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Section 1
INTRODUCTION

The preliminary designs of Stationkeeping Subsystems (SKSS) for the OTEC Modular Experiment Plant are being prepared for a barge and spar platform. The SKSS selected by NOAA for the barge is a multiple anchor leg mooring with active tensioning (MAL), while that for the spar is a tension anchor leg (TAL) moor. The development and testing program required to provide design data and to validate performance predictions are treated in this report.

Basic assumptions are made with regard to site characteristics, behavior of the SKSS and platform in the sea state, and characteristics of SKSS components. The test program is intended to provide the data necessary to confirm assumptions or to support design revisions.

With respect to the site it is assumed that:

1. Bottom geology and consistency is suitable for the effective use of drag-embedment anchors.
2. The bottom is planar and clear of obstructions at the anchor implantation locations.

Regarding specific aspects of preliminary design, it is assumed that:

1. Quartering seas generate worst-case loads in the MAL SKSS.
2. Platform loading and SKSS response to long period seaway phenomenon are represented by an equivalent steady force and resultant offset.
3. Dynamic tensions in the MAL are 10 percent of maximum static tension.
4. Design of windlasses for anchor deployment and mooring leg loads requires only a reasonable extrapolation of current practice and, therefore, a windlass development effort is not recommended.
5. The continuous pulling machine to be used aboard the deployment barge does not require development effort.

6. The unjacketed wire rope is capable of providing a minimum of 10 years service life.
7. The service life of the specified anchor and chain is a minimum of 30 years.
8. Barge heading changes by means of mooring leg active tensioning are representative of current practice and do not require development.
9. The drag embedment anchor can be set to an accuracy of ± 50 ft.
10. Fatigue cycle data for wire rope in air is assumed to apply to wire rope in seawater.

Assumptions which are not treated in this plan that require further investigation are:

1. Sea states, including seaway, wind, and ocean current conditions, and earthquake activity are limited to those described in government-provided criteria.
2. All sea state forces acting on the platform are co-planar.

Predictions of MAL SKSS performance and sea state response are presented in the Task III Preliminary Design Report.

The testing program for the multiple anchor leg system is considered first, followed by the tension anchor leg program. Development and testing are recommended in the areas of materials, components and procedures which are beyond modest extrapolation of current ocean engineering practice.

In the case of materials and components which are within the present state-of-practice, it is intended that standard certifications are provided and non-destructive testing, such as radiographic, dye-penetrant, or magnetic flux inspection, are conducted by the vendor to assure product quality. Manufacturing acceptance, proof load, and/or functional demonstration tests are performed in accordance with normal industry and vendor practices. This type of standard testing is not treated further in this plan.

The current depth record for deployment of a multiple anchor leg mooring is 3,461 ft held by the Discoverer 534 drillship with turret. The OTEC platform displacement is approximately three times greater than that of the exploratory drill ship. The largest wire rope in use as anchor line is 3.5 in. diameter, although 11 in. diameter wire rope has been used for slings to lower a single anchor leg mooring base in the North Sea. The duration of deep water moors is generally on the order of weeks as compared to 30 years for the permanent OTEC installation. Mooring winches and sheaves have been built to accommodate 3.5 in. wire with lengths to at least 3,500 ft. Mooring windlasses capable of handling 4-3/4-in. anchor chain are in operation on aircraft carriers. Single anchor leg moorings, analogous to the tension anchor leg SKSS, are designed for twenty year life and have been deployed in water depths up to 500 ft. These systems incorporate a universal joint attached to a base structure on the seafloor. Tension anchor leg platforms for offshore oil production are in the design development stage for water depths beyond 1000 ft. There appears to be a current lull in construction in the offshore industry and major advances in hardware development are not anticipated in the next few years. Consequently, design of the OTEC SKSS for deployment in 1984 is assumed to rely on present or modest extension of current practice in this industry.

Section 2
DEVELOPMENT AND TEST PROGRAM FOR MULTIPLE ANCHOR LEG (MAL) SKSS

It is recommended that MAL SKSS test activities be planned for accomplishment in three major categories. These consist of development testing early in the design program to confirm design assumptions, hardware tests for verification and evaluation of critical components of the proposed system; and finally full-scale exercises in the construction phase to check the functional integrity of selected system elements and to evaluate the techniques for deployment.

2.1 DEVELOPMENT TESTING

2.1.1 Seafloor Sampling and Profiling

Measurement of soil properties and the geologic structure of the ocean bottom at each of the eight anchor implantation sites is key to confirming the suitability of drag-embedment anchors. It is recommended that a site survey to define these characteristics be conducted before the next phase of SKSS design. Seismic surveying techniques are used to determine the sub-bottom profile. Soil depths of two to five times anchor height are required for drag embedment anchors. In the event that shallower depths are observed, then alternatives to the drag embedment anchor such as drilled and grouted pile anchors are required depending on the as-measured conditions. Alternatively, adjacent areas of the seafloor are surveyed for sites appropriate to drag embedment anchors. Core samples are required at each of the anchor locations to determine angle of internal friction, bearing capacity, density, shear strength, consistency, and sediment content. Data may be obtained using Doppler penetrometers at each location. In order to assess the potential fouling risk to the anchor legs and electrical riser system from sea floor obstructions, a side scan sonar survey of the area is also required. An assessment of the reduced data is required to determine suitability of drag embedment anchors, anchor set distance, and holding power.

2.1.2 Scale Model Tests

In order to evaluate response of the OTEC barge and SKSS in design sea states and modes of operation it is recommended that a 1/50th scale model of the barge be prepared and tested together with moorings which simulate the design and dynamic characteristics of the MAL SKSS. This test is recommended as a source of data for use in evaluating the critical design assumption of coupled barge-SKSS seaway response.

Data are obtained defining motions, excursion limits, and mooring leg tensions when the barge model is exposed to regular and random wave spectra. Of particular interest is dynamic excursion and anchor leg tension due to slowly varying wave drift force and moment. To this end long period wave groups are modeled which simulate likely occurrences at the site. Wave heights are varied up to a scaled equivalent to the Extreme Sea State with heading varying from bow-on to astern, port and starboard. In addition, mooring leg loads are determined under conditions simulating active tensioning to verify that this technique optimizes tension loadings. This is accomplished by variation of anchor leg length in the conduct of the test program. Analysis of the data obtained is performed to confirm SKSS and barge loads and response characteristics. In particular, long period mean tension and excursion are examined to assess the effects of slowly varying wave drift force and moment on the barge and SKSS.

Model testing is based on Froude scaling. A more detailed discussion of this together with scaling factors is found in Section 3.1. For a model scale of 1:50 the Extreme Sea State significant wave height is 15.2 in. The barge includes a model of the CWP to a depth of approximately 60 percent of the maximum wave length or 10.5 ft in scale. Barge principal dimensions, weight, buoyancy, and mass moment of inertia, including the CWP, are modeled. A number of test basins exist which have the capability of modeling the desired environment (see Table 3-1).

Figure 2-1 illustrates a model of a ten-leg MAL SKSS at a scale of 1/3600.

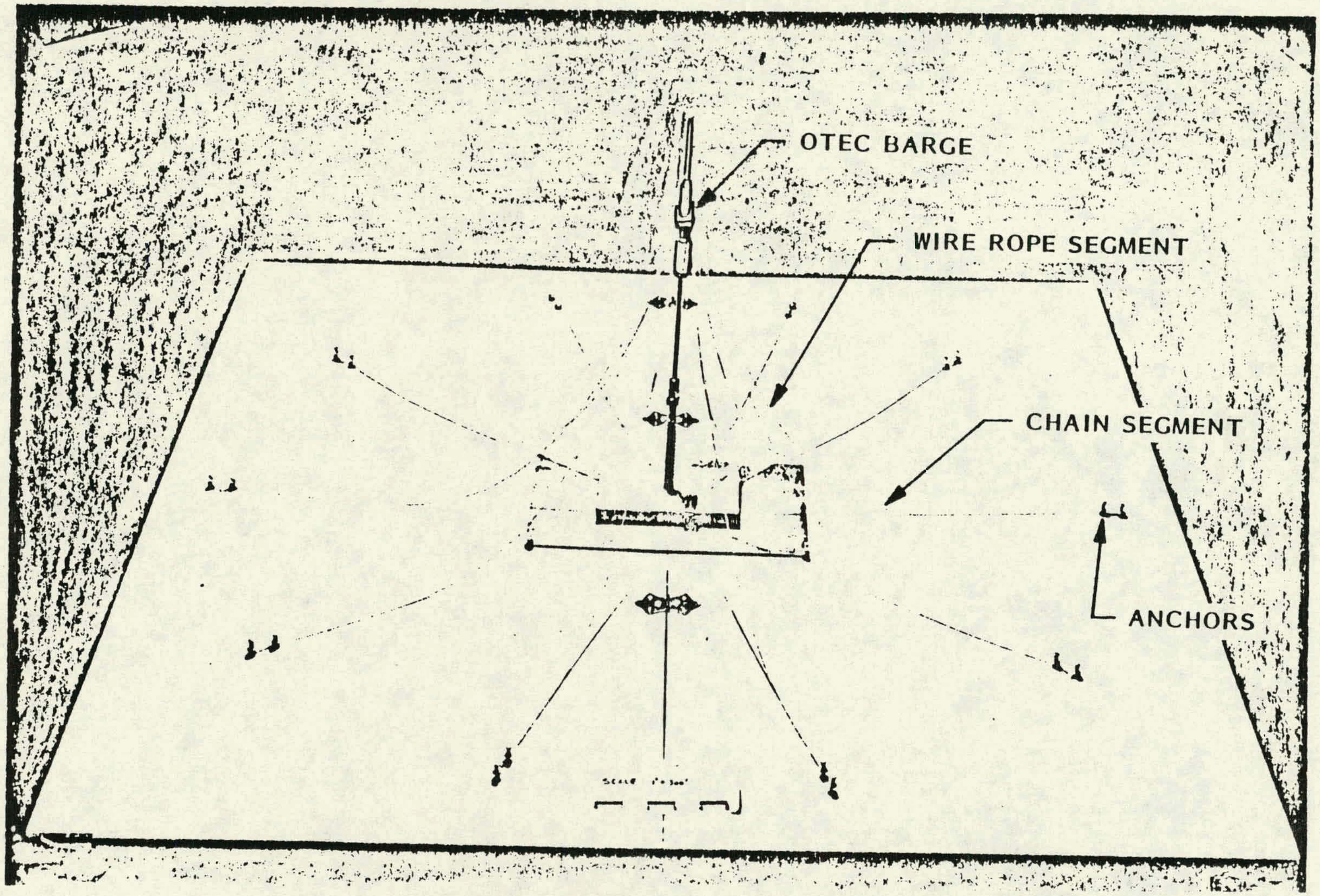

Fig. 2-1 Multiple Anchor Leg SKSS

2.1.3 Service Life Improvement Tests

Testing to evaluate the possibility of handling plastic sheathed wire rope, while not specified for the preliminary design, is recommended as a potential means of extending the wire rope service life. A sheathing is sought which meets the requirements of protecting the wire rope from corrosion and which can pass through the continuous pulling machine without detrimental effect to its covering during deployment and change-out. The following characteristics are considered: crush strength, resistance to seawater, flexural strength and life, resistance to abrasion, bond strength, density, hardness, optimum thickness, and susceptibility to biofouling damage.

2.2 HARDWARE TESTS

Hardware-type testing is necessary for the wire rope section of the anchor leg. While wire rope is produced in larger sizes and load ratings than that required for the MAL SKSS, relatively little is known with respect to corrosion and fatigue life in long-term ocean deployment. In order to establish the wire rope service life, it is necessary to conduct an extensive testing program prior to the next phase of SKSS design. In addition to separate corrosion tests and fatigue tests, combined testing is required to evaluate wire rope fatigue in seawater. In discussions with wire rope manufacturers it is clear that a cooperative, cost sharing venture is required for a program of this nature. For example, a program with Fatzer, A.G. would utilize existing facilities in Zurich, Switzerland, extensively involved in wire rope testing for aerial tramway systems. Availability of this facility and expertise provides a potentially lower cost effort than a similar program conducted in the United States.

In conjunction with the wire rope corrosion testing, it is recommended that an investigation be conducted into the potential advantages of using epoxy resin materials in place of the zinc conventionally used to fill socket connection fittings. Use of the more inert epoxy in place of the electrochemically active zinc may provide greater corrosion resistance. Long-term stability and strength of the epoxies in the deep sea environment needs to be established.

Chain capacity to provide adequate fatigue and abrasion strength for a 30-year service life requires further investigation. Chain testing is required if adequate data is not available on performance of chain in large diameter chain in deep ocean mooring. Tests exploring corrosion properties are conducted in seawater having chemical constituency, physical properties, and average temperature range which simulate those characteristics at the deployment site.

2.3 FULL-SCALE EXERCISES

In this category are included activities to be conducted involving SKSS elements for the purpose of verifying functional integrity of related components and confirming the suitability of designs and techniques for SKSS handling and deployment.

2.3.1 Anchor Assembly Test

A full-scale test is recommended to confirm that the tandem anchor assembly, consisting of the two 60,000-lb drag-embedment anchors and their connecting chain segment, can be set with proper orientation and embedment on the ocean bottom. This test, following the soils test and preceding detail design, also provides the opportunity to measure the lateral travel necessary for the assembly to achieve full embedment. The benefit of the test is to provide data to verify the concept of tandem anchors and to validate the techniques for predicting anchor set distance, essential to proper placement of the anchor assemblies during actual deployment at the operational site. As a secondary benefit, this test provides experience with which to refine the anchor deployment technique.

The anchor assembly test is conducted at a site which has known bottom characteristics, preferably similar to those of Punta Tuna, P.R., with respect to slope, soil material and sufficient depth for full embedment. To help hold costs down, minimize handling problems, and facilitate observation of test results, a suitable site in relatively shallow water depth (300 to 500 ft) is recommended. The use of subscale models for this test, conducted prior to procurement of the full-scale hardware, reduces program risk and is recommended for further investigation.

Required in addition to the anchor assembly are:

1. Sufficient chain to provide a minimum 6 to 1 scope.
2. A deck barge with a deadweight of approximately 6000 tons.
3. Unmanned submersible equipped with closed circuit television and acoustic or sonar transponder.
4. Submersible support vessel, 160 ft length.
5. OTEC SKSS deployment windlass or equivalent mounted on crane barge.
6. 5700 hp anchor handling tug/utility vessel, 190 ft length, approximately 150,000 lb bollard pull
7. Anchor trip lines and buoys.

The anchor assembly, with a chain rope of adequate length to provide a 6 to 1 scope as a minimum, is lowered to the sea floor using the intended deployment technique. Underwater surveillance of this operation is maintained by use of closed circuit TV on an unmanned tethered submersible. The proper chain scope is payed out and the barge carrying the deployment windlass is securely moored. The windlass is then operated to set the anchors while continuing TV surveillance. Measurement of embedment travel is made, as well as line tension continuity for a specified period of time. The anchors are retrieved using individual trip lines previously attached.

2.3.2 Deep Water Handling Test

This test has a two-fold purpose. First, it provides an opportunity, well in advance of OTEC mobilization, to evaluate the deployment system and its components. Second, it permits assessment of the procedures to accomplish this previously untried task. This test is conducted by the deployment contractor following completion of the OTEC SKSS deployment barge.

The operation of paying out the wire rope segment, lowering the anchor assembly and chain segment to the bottom, and making up the chain-to-wire connection is conducted with a single anchor leg of the MAL SKSS. The anchors are not set. The entire mooring leg is recovered at the completion of this operation. In addition to the mooring leg, the following are required:

1. A deck barge of approximately 6,000 dWT capacity.
2. OTEC SKSS deployment winch and windlass equivalent mounted on crane barge.
3. Anchor handling tug/utility vessel of 7,800 hp and 218 ft length.
4. Anchor trip lines and buoys.
5. Unmanned submersible equipped with closed circuit TV.
6. Submersible support vessel, 160 ft utility boat.

2.4 SCHEDULE AND COST ESTIMATES

Estimated schedule and costs for each test described in the previous section are presented with basis of estimates in this section, and summarized in Table 2-1. All costs are stated in 1979 dollars.

Table 2-1 SUMMARY OF MAL SKSS TESTING COSTS AND SCHEDULE

Test	ROM Cost ($K)	Schedule (Days)
Seafloor Sampling and Profiling	125	15
Scale Model	40	7
Service Life Improvement Tests	128	730
Hardware (Wire Rope) Tests	100	270
Anchor Assembly	105	5
Deep Water Handling	220	6

2.4.1 Seafloor Sampling and Profiling

Bottom soil profiling studies, core sampling and side scan sonar mapping of the anchor emplacement area is estimated to be $125,000 ROM including a 160 ft support vessel and the scientific services required. This is based on a vessel transit time to the site of four days, survey activities for seven days and a return trip of four days. The cost of each Doppler penetrometer drop is $1,500.

2.4.2 Scale Model Tests

Model test operations are estimated to require one week of occupancy in a facility such as the Offshore Technology Corp. test basin. The ROM cost for this activity is $35,000. In addition, model fabrication cost is estimated at $5,000.

2.4.3 Service Life Improvement Tests

Actual time spans and expenditures for development testing as described in Section 2.1.3 are difficult to estimate due to the number and type of variables involved and the intangible influences possible, such as development of new materials or processes by others. It is felt, however, that even an accelerated exposure and aging program requires a 2-year span. Over that period of time a researcher half time assisted half time by a technician is estimated to cost $38,000/year. Materials and supplies are estimated to add $25,000/year for a total ROM cost of $128,000.

2.4.4 Hardware Tests

On the basis of a shared cost venture as discussed with wire rope fabricators, the ROM cost of fatigue and corrosion tests is $100,000 and a 10-month span is required.

2.4.5 Anchor Assembly Test

Assuming that a test site is selected which requires a 2-day transit from the staging port, that the deployment barge is outfitted and that test activities require 3 days, it is estimated that vessel, fuel, crew, and equipment leasing costs are approximately $105,000.

2.4.6 Deep Water Handling Test

It is assumed that the deployment barge used in the previous test is used for this operation and that the test will take place directly following the anchor assembly test with a 1-week staging period. It is further assumed that the selected site requires a 4-day transit from the staging port and that test activities require 2 days. Cost of vessels, fuel, crew and equipment leasing is estimated at $215,000. Ocean Systems observers (2) are estimated at $5,000. Total ROM cost is approximately $220,000.

Section 3
DEVELOPMENT AND TEST PROGRAM FOR THE TENSION ANCHOR LEG (TAL) SKSS

The Task III Report presents a preliminary design for the Spar-TAL SKSS, based on a set of design loads derived from a simplified load analysis. These loads require verification by model tests prior to a detailed design. The measured motions and response of the spar and CWP are then compared both qualitatively and quantitatively with the results of the simplified analysis.

The loads on the mooring base are all that are required from the model tests for the design of the TAL-SKSS. Since the spar and CWP must be modeled correctly to reproduce the desired base loads, it is necessasry to monitor the loads and response of the entire system. In this report, an integrated model test program is described which provides the necessary information for the design of major components of the Spar-TAL. A design iteration of the CWP is recommended so that the Spar-TAL configuration is integrated prior to testing.

3.1 MODEL TESTING

Model tests have played an important role in the design of offshore structures presently in use throughout the world. The validity of model testing is established for a great variety of offshore structures such as semisubmersibles, mooring systems, and offshore platforms. Model tests are used to prove the feasibility of new concepts, to verify load analysis techniques and computer programs, and to provide design loads for a specific design.

Model tests of the Spar-TAL are required prior to a final design. These tests provide a set of loads for further design and can provide verification of computer programs, such as ROTEC (Dr. R. Paulling) and the NOAA/DOE program, used to simulate the spar and CWP.

3.1.1 Froude Scaling

Model tests of most offshore structures are based on Froude scaling. The Froude number is the ratio of the inertia force to the force of gravity. Froude scaling is based on the fact that the density of water and the gravitational acceleration are the same for the model as for the full-size structure. (A small correction is made for the difference between the density of fresh water in the tank and salt water in the ocean.) Froude scaling is valid for large structures such as the Spar-TAL because the major forces are caused by buoyancy and wave inertial forces, which are modeled correctly. The Reynolds numbers for wind and water motions are not modeled, but the resulting drag forces are approximately modeled correctly because the drag coefficients are fairly constant at the high turbulence ranges typically encountered.

If the model scale is 1/N, the remaining variables scale as follows:

Distances, Lengths	1/N
Density	0.975*
Acceleration	1
Forces and Weights	$0.975/N^3$*
Time	$1/\sqrt{N}$
Angles	1
Velocity	$1/\sqrt{N}$

*0.975 is a correction for fresh to salt water

3.1.2 Selection of a Test Facility

The large water depth required for an OTEC plant limits the number of model test facilities that could test the Spar-TAL. Tests of a spar without the cold water pipe are discussed on page 21. Without a deep basin, the model scale would be too small for accurate results. Very small water waves are capillary waves and do not model as well as the usual gravity waves.

A list of test basins and their maximum water depth is provided in Table 3-1. This list includes the facilities commonly used by private industry for the testing of offshore mooring systems. Government or military sponsored facilities are not listed because several industry facilities are available.

The proposed model test facility for testing of the Spar-TAL is Offshore Technology Corporation (OTC) located in Southern California. This facility, with a deep tank and excellent wave generator, is experienced in the modeling of single-point mooring systems. Although this report is written with the OTC facility in mind, a final model test specification could be written and submitted to several test facilities for competitive bids and for a comparison of different modeling approaches. This would add approximately 6 weeks to the test schedule.

The model basin at OTC is 295 ft long, 48 ft wide, and 15 ft deep. A pit in the middle of the basin, with a total depth of 30 ft, allows testing of deep water systems. Waves are produced by a wave flap driven by a servo-controlled hydraulic piston. Computer-derived irregular wave spectra, such as Pierson Moskowitz, are stored on magnetic tapes that are used to drive the wave

Table 3-1 TEST FACILITIES

Test Basin	Location	Maximum Depth (ft)
OTC	Escondido, CA	30
NSMB	Netherlands	18
SOGREAH	France	Approx. 9
NMI	England	25
Marine Dyn. & Ship Lab.	Ottawa, Canada	15
SSPA	Sweden	16.5
Hydronautics	Laurel, MD	35
Ship Research Institute	Mitaka, Tokyo, Japan	15

generator. These spectra are plotted and compared to the desired spectra; favorable comparisons are usually obtained for the higher significant wave heights. The spectra are comparable or superior to those produced in other private test facilities.

Wind is usually provided by a set of fans mounted near the water surface. Current can be provided by a pump and nozzle-pipe arrangement that can be adapted to various current orientations.

3.1.3 Modeling

Model Scale. The Spar-TAL system, shown in Fig. 3-1, can be tested at OTC at a scale of 1/120. This is a smaller scale than usual for mooring systems. The 3,280-ft water depth scales to 27.33 ft, which allows extra freeboard in the 30-ft pit for waves.

The maximum wave height of 63.2 ft becomes 6.3 in. with a significant height of 3.5 in. The wave accuracy is slightly reduced because of the small size, due to wave-making and measuring errors. Repeat tests may be necessary to obtain the correct wave height. The lower half of the pit effectively blocks wave activity on the lower half of the cold water pipe (CWP), but very little wave motion occurs at that depth.

Random waves of various heights are used in the tests. Regular waves with various periods are required for several tests. All significant wave heights are to be within 10 percent of the requested value.

The 2.4-knot surface current scales to 4.4 in./sec. The pipe-nozzles are placed in a vertical line to provide current along the length of the CWP. The nozzles are placed so as to provide a varying current with depth. The small model scale means that the Reynolds number shifts from the turbulent range for the full-sized CWP into the subcritical range for the model tests. Current forces are therefore higher in the test basin, unless the current velocity is scaled down to compensate for this effect.

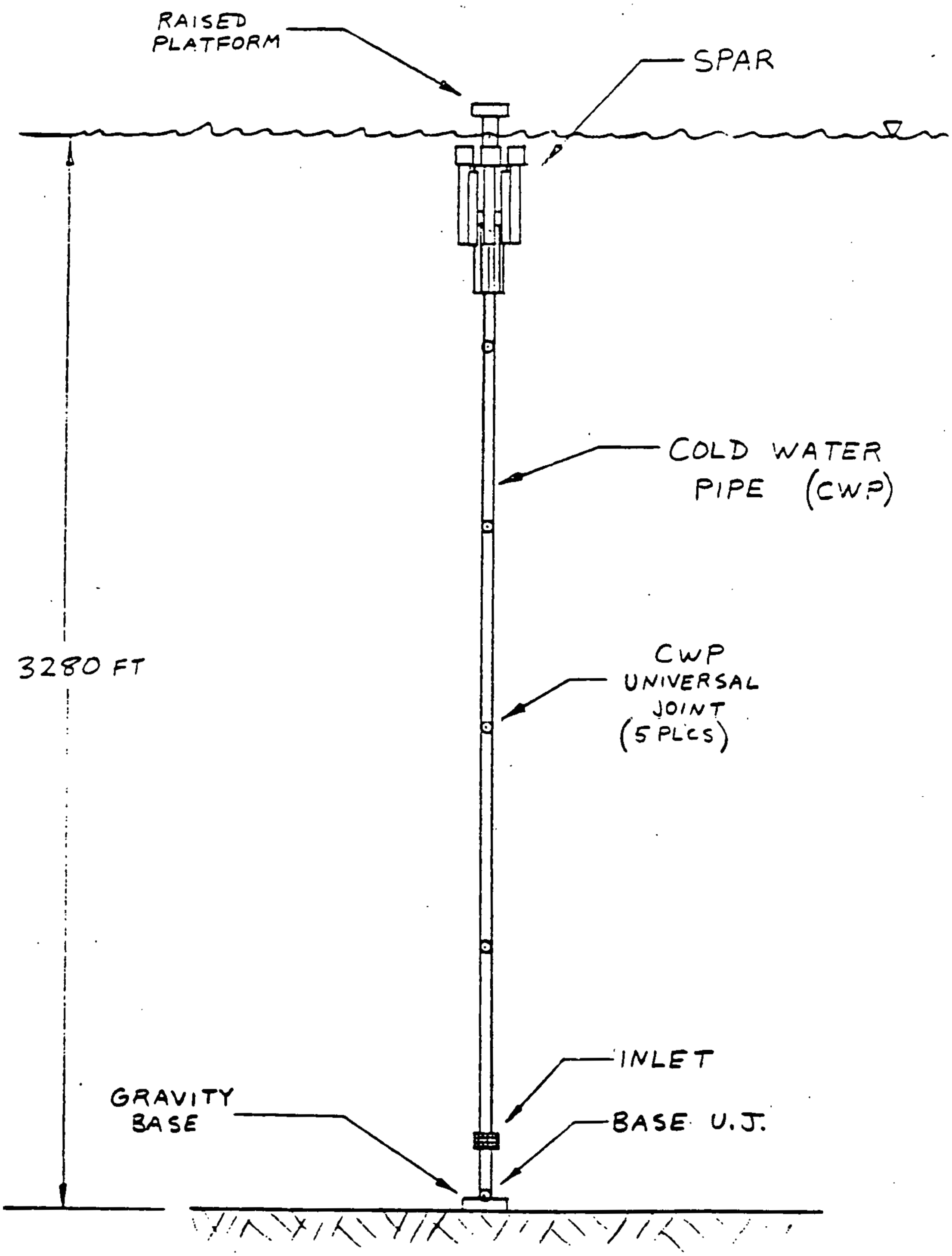

Fig. 3-1 OTEC Spar-TAL

Wind is provided by a single fan on the surface. The wind will be in the same direction as the waves. An accurate anemometer is used to determine that the velocity pattern of the wind over the swing area of the spar is appropriately modeled. The wind mean and standard deviation, if not steady, is required to match the properties of a real wind field. Wind is measured at a point 30 ft full scale above still water. Strip charts of the wind velocity are provided. For simplicity, the wind force could be modeled by a string, weight, and pulley arrangement. However, the wind force is small compared with wave and current forces, and may be ignored in these tests if desired.

Model Construction. All models and test equipment are furnished by the test facility. Drawings of the models, showing method of construction and instrumentation, are approved by the contractor prior to model construction.

Spar Model. The spar is modeled as shown in Fig. 3-2. The outer dimensions, the configuration, the weight, the buoyancy, and the mass moment of inertia are modeled. The spar is of solid watertight construction with variable solid ballast. A low-friction ball or universal joint connects the lower end of the spar main body to the CWP. Structural stiffness of the spar is not modeled.

CWP Sections. The diameter, bending stiffness, axial stiffness, and underwater weight per foot is modeled as shown in Fig. 3-3 and Table 3-2. The density of the material is preferably similar to the density of steel. The interior of the CWP sections is hollow and flooded with water during the tests. The ball joints or universal joints at either end of each section are as frictionless as possible. The center of gravity of each section lies along the centerline axis.

CWP Buoyancy Section. The top section of the CWP includes a buoyancy chamber. The geometry, dimensions, net buoyancy, and weight are modeled. Stiffness is not modeled.

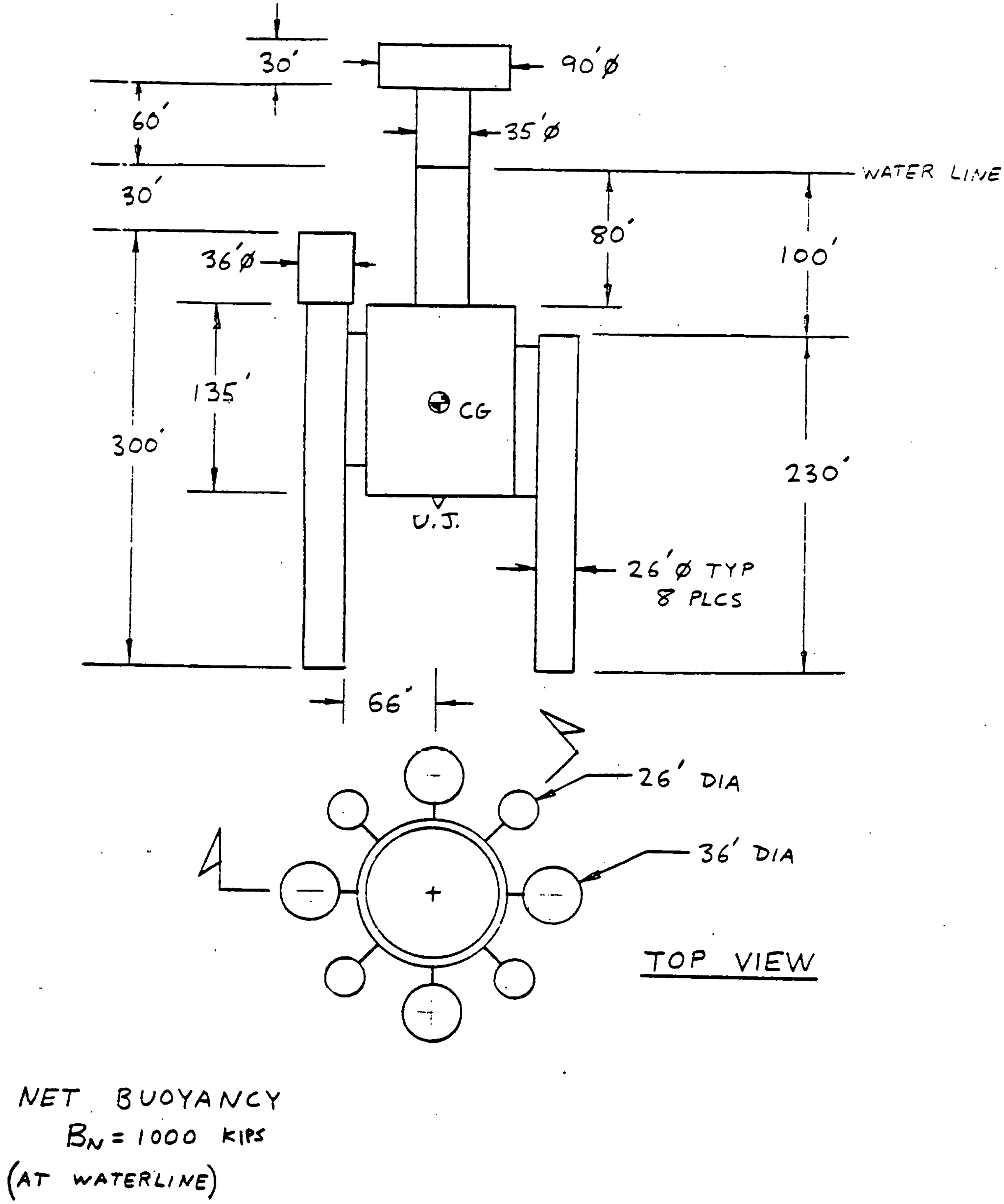

Fig. 3-2 Spar Configuration

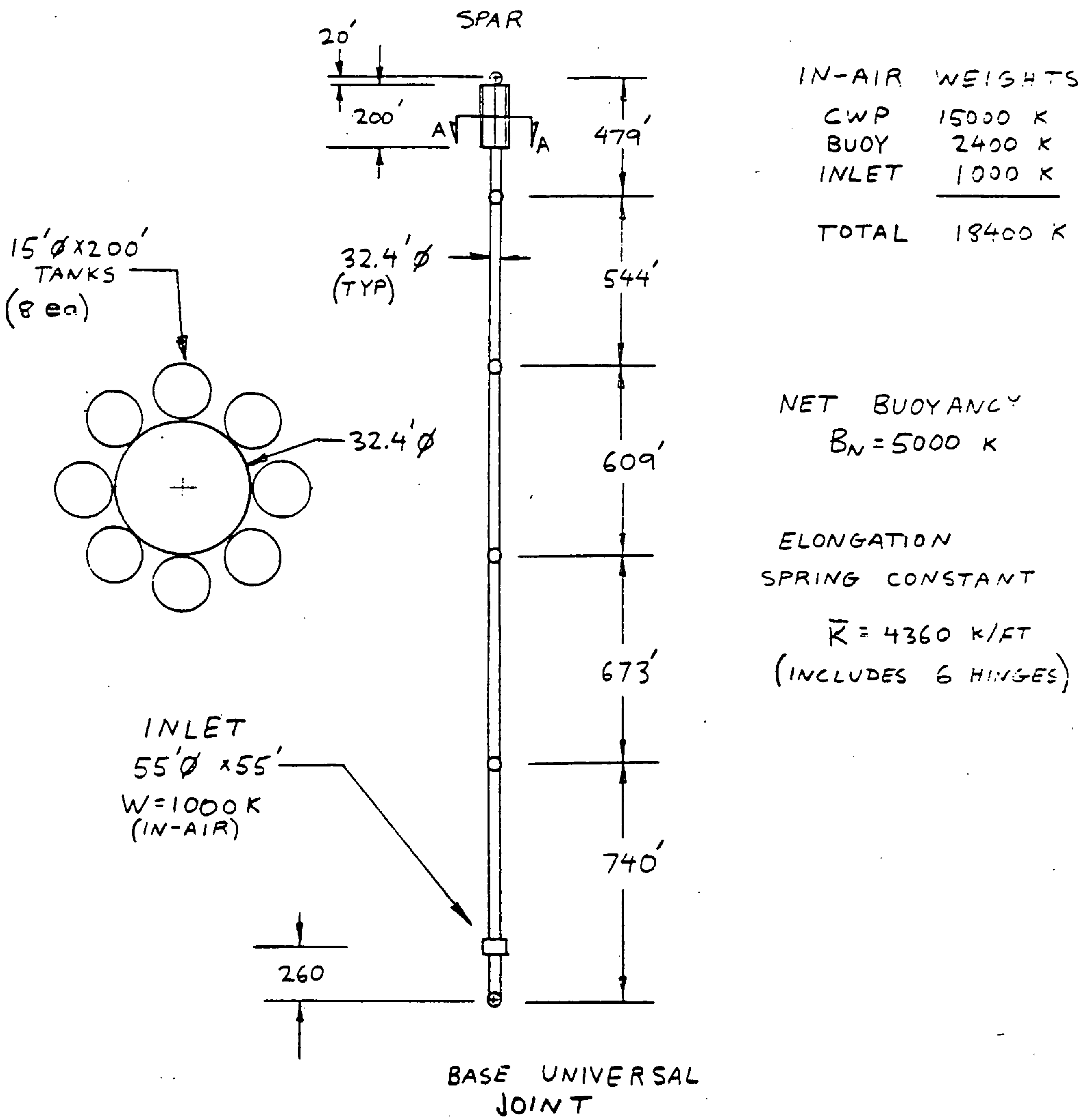

Fig. 3-3 CWP Configuration

Table 3-2 CWP MODEL

Seg No.	Length (ft)	Outer Diam (ft)	In-Air Wt/Ft (lb/ft)	d* (ft)	Total Buoyancy (lb/ft)	Top	Bot
1	20	32.4	4926	0	645	B	F
2	200	32.4 +8 x 15	16926	20	107100	F	F
3	259	32.4	4916	220	645	F	B
4	544	32.4	4926	479	645	B	B
5	609	32.4	4926	1023	645	B	B
6	673	32.4	4926	1632	645	B	B
7	740	32.4	6283	2305	823	B	B

*d = distance from CWP upper pivot to top of segment
B = ball joint
F = fixed

CWP axial stiffness = 4360 kips/ft

All dimensions full scale

Mooring Base. The mooring base is not modeled. The universal joint between the base and the lowest CWP section is modeled as a low-friction universal joint.

Simplified Spar-TAL. Model tests could be conducted without the CWP by providing a set of vertical and horizontal springs to model the CWP axial stiffness and the buoyancy restoring force. This model would demonstrate the heave motions of the spar. The analysis in the Task III Report, however, shows that damping is very important in limiting the spar heave resonance. The above simplified model does not provide a definitive value of damping and is therefore of little use in deriving design loads.

3.1.4 Instrumentation

Transducers are arranged to measure the following variables:

- o The three perpendicular forces acting on the upper CWP pivot, referenced to the spar
- o The six motions of the spar: pitch, roll, yaw, heave, surge and sway, referenced to its center of gravity
- o The two perpendicular bending moments in the middle of each CWP section, five sections in all
- o The three perpendicular forces acting on the mooring base, one vertical and two horizontal
- o The two perpendicular angles at the base universal joint, measured from the vertical
- o The wave surface elevation

These variables are demonstrated in Fig. 3-4 and Table 3-3.

The spar motions are required for the design of the OTEC subsystems as well as for computer program verification. The primary spar response motions are heave, surge, and pitch. Roll, yaw, and sway is less pronounced because no wave force excitations occur in their respective directions. In model testing, as in full scale, there is some motion in these secondary directions, and these motions are measured in case they are needed for design, and to prove that they are noncritical. Since the torsional rigidity of the CWP is not modeled, the yaw response will be the least reliable motion variable.

The measurement of the six spar motions is difficult to accomplish without affecting the spar motions. One solution is to fabricate a lightweight motion sensing transducer (MST) for attachment to the spar platform. An extra test can be conducted without the MST to check its effect on the system response. The motions can also be measured photographically, but this is a tedious process. An alternative approach is use of miniaturized acoustic transducers developed for automatic focusing cameras. These transducers provide monitoring of the spar and CWP motions.

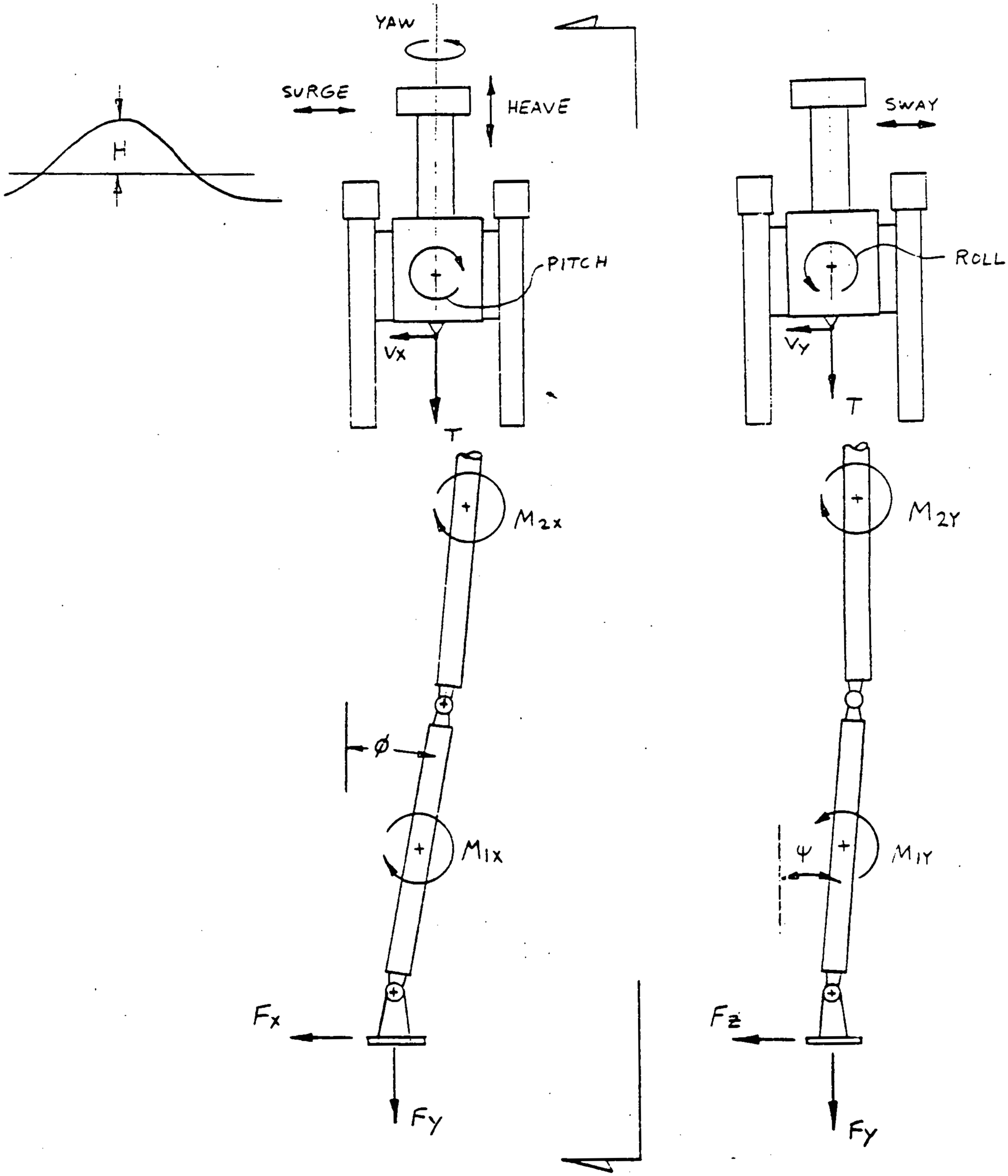

Fig. 3-4 OTEC Spar-TAL Transducer Arrangement

Table 3-3 TRANSDUCER LIST

Variable	Name	Transducer Range (Full-Scale)	Oscill	Remarks
Spar-CWP Tension	T	0-60000 K	Yes	WRT Spar
Spar-CWP X Shear	V_x	± 10000 K		WRT Spar
Spar-CWP Z Shear	V_z	± 10000 K		WRT Spar
Base Vertical Load	F_Y	- 1000 K + 60000 K	Yes	
Base Horiz X Load	F_x	± 5000 K	Yes	
Base Horiz Z Load	F_z	± 5000 K		
Base UJ Angles		± 30 deg		
		± 10 deg	Yes	
CWP Moments	M_{1X} M_{1Y} M_{2X} M_{2Y} M_{3X} M_{3Y} M_{4X} M_{4Y} M_{5X} M_{5Y}	± 500000 K-ft	Yes	
Spar Heave	Heave	± 30 ft	Yes	
Spar Surge	Surge	± 500 ft		
Spar Sway	Sway	± 200 ft		
Spar Pitch	Pitch	± 20 deg		
Spar Roll	Roll	± 20 deg		
Spar Yaw	Yaw	± 30 deg		Yaw response not modeled

K = 1,000 lb

3.1.5 Measurements

The sensitivity, the precision and estimates of the accuracies of all instruments are to be provided. Each transducer is calibrated and calibration charts are prepared before commencing the tests. Expected maximum values are provided in Table 3-3. The transducer locations are shown in Fig. 3-4. Measurements of variables listed in Table 3-3 are recorded continuously during the test.

The test setup at OTC allows several variables to be combined mathematically after a test. These combined variables produce new dependent variables which aid in design work. Several possible combinations of variables are shown in Table 3-4.

The mean wave drift force is measured at the base and is simply the mean horizontal base load. For tests without wind and current, this mean base load is equal to the mean wave drift force on the spar and CWP. The slowly varying wave drift forces on the spar system cannot be measured by the proposed transducer arrangement. An entirely different model design is required, in which the long period drift motions would be restrained, thereby allowing measurement of the time-varying drift forces.

3.1.6 Test Requirements

The time duration of the record and number of points of measurement are noted during each test. Data for 30 minutes of full-scale time (3 minute model scale) are recorded by the computer for each test in irregular waves. Steady state environmental con- ditions are attained prior to recording data for any test. All transducer readings are zero during still water conditions. All data are to be analyzed, including repeated tests. The approximate total time duration of tests is 60 minutes, and the statistics for prediction of response in any particular sea state is based on this full set of data.

Data, for approximately 10 minutes of full-scale time, are recorded for all regular wave tests. Standard test reduction is performed with regular wave data, such as average, maximum, minimum, and peak average.

Table 3-4 COMBINED VARIABLES

Variable	Combined Variable
T_{sum}	$\sqrt{T^2 + V_x^2 + V_Z^2}$
P_{base}	$\sqrt{F_x^2 + F_Y^2 + F_Z^2}$
θ base	$\theta_B = \cos^{-1} (\cos \phi \cdot \cos \psi)$
M1	$\sqrt{M_{1X}^2 + M_{1Y}^2}$
M_2 etc thru M_5	similar to above
V_{spar}	$\sqrt{V_X^2 + V_Z^2}$

For each test, an oscillograph record, covering 5 minutes of full-scale time, is made. A sufficiently rapid chart speed is used to permit easy identification of each trace. Zero lines are run before each test. All strip charts are to be presented after completion of the test report. Variables to be recorded are shown in Table 3-3.

Before the start of the tests, a static force deflection relationship is measured. Static deflection tests with the following variables recorded are performed:

V_x
T
F_y
F_x
Surge
Pitch
Heave
M1X thru M5X

These tests are performed by pulling horizontally with a string attached to the spar. The force in the string need not be measured.

Natural periods of several modes of oscillation of the SKSS are measured before the tests. These include the pitch, heave, and surge periods. If the motions are highly damped, then a manual excitation is used to estimate the approximate natural period.

Selected data are presented graphically, in addition to the tabulation of all resulting data. Observations made during the tests shall be recorded, to assist in the interpretation of the numerical results. Attempts are made, where possible, to explain the results from a physical viewpoint.

Color photographs are taken during each test. Color photographs are made of the models. High speed 16mm color motion picture films are taken of tests when required. Camera speed is set to simulate real time when shown at 24 frames/second.

In addition to movies taken above the water, underwater movies are required. The view is perpendicular to the wave motion. These movies are used to analyze the CWP motions in conjunction with the motion data obtained by the acoustic transducers.

Data Reduction and Records. For all loads and angles, the following values are computed for irregular wave tests:

Mean
Standard Deviation
Significant Value
Maximum Recorded
Minimum Recorded

RAO curves are generated for a flat spectra random sea. Response spectra for all variables are computed for several tests.

Report. Within 30 days of the conclusion of the test program, 12 copies of the report shall be delivered. A one-page summary sheet prefaces the report to aid in future reference to the tests.

Test Computer Tapes. The data from all completed tests shall be stored on large industry standard tapes (MAGTAPE).

3.1.7 Program Schedule

A proposed test schedule is shown in Table 3-5. These tests provide sufficient data to derive design loads and to aid in verifying the OTEC CWP computer programs.

The first two test series check the effect of current and wind on the system response. After it is determined whether wind and current increase or decrease the loads, the remaining tests are run with or without current as required to produce the highest loads. Design loads are based on a statistical distribution of the results of all tests, including repeat tests. Thus it is desirable to run tests under a range of conditions.

Table 3-5 TEST SCHEDULE

Test No.	H_{reg} (ft) $H_{1/3}$	Period (sec)	Surface Current (knots)	Wind (knots)	Remarks
1	18.9	BS	1.8	29.5	Operational
2	18.9	BS	0	29.5	Operational
3	18.9	BS	0	0	Operational
4	35.1	BS	2.4	82	Storm
5	35.1	BS	0	82	Storm
6	35.1	BS	0	0	Storm
7	10	BS	1.8	0	Fatigue
8	10	BS	0	0	Fatigue
9	10	6	*	0	
10	20	8	*	0	
11	30	10	*	0	
12	40	13	*	0	
13	50	13	*	0	
14	60	13	*	0	
15	30	18	*	0	

BS = Bretschneider irregular wave

*To be decided during tests

Variables full scale

Cost and Time Schedule. A rough cost estimate and time schedule for these model tests is provided in Table 3-6. The total model test program cost is approximately $43,000. The schedule requires 6 weeks of test preparation and 2 weeks of testing. The dates of testing are subject to facility availability.

3.2 OTEC COMMERCIAL PLANT

The model test program and procedure is nearly identical for the OTEC Commercial Plant as for the Modular Experiment Plant. The models are of a different size and the transducer ranges are higher to accommodate the higher loads. The model scale, test procedure, and transducer arrangement are the same.

3.3 COMPONENT TESTING

Besides model testing of the overall Spar-TAL system, tests of various components are conducted to ensure safe operation of the OTEC SKSS. These tests are summarized in this subsection.

3.3.1 Universal Joint

The base CWP universal joint is rotated after fabrication to check the clearances of the structure so that it does not bind during operation. The torque required to turn the bearings is measured. The costs of these tests should be included in the fabrication costs.

3.3.2 Mooring Base

Lowering the mooring base during installation is fairly straightforward analytically; therefore model tests are not required. Heave resonance of the base on its lowering cable will be avoided.

Table 3-6 MODEL TEST COST AND SCHEDULE ESTIMATE

I. COST

The cost estimate for the model test program is as follows:

a.	Models	
	Model, construction and ballasting to customer plans and specifications (6 weeks required)	$ 3,000.00
b.	Pre-test engineering	2,000.00
c.	Test setup and testing (2 weeks)	
	10 shifts @ $2,500.00/shift	25,000.00
	Installation and removal of wind generators	250.00
	Installation and removal of current generators	500.00
d.	Instrumentation	
	25 data channels @ $160.00/channel	4,000.00
	9 derived channels @ $160.00/channel	1,440.00
e.	Data reduction and twelve copies of report	3,000.00
f.	Photography	
	2,000 ft of 16mm color motion pictures	4,000.00
	TOTAL	$43,190.00

II. SCHEDULE

a. Total time required — 8 weeks

b. Test dates subject to basin availability

3.3.3 Installation Tests

The installation of the Spar-TAL may require model testing, depending on the procedure selected. These tests can provide dynamic loads as well as static response.

Scale models of installation aids may be made to verify the concepts and to aid in instructing installation personnel. For example, scale models have been made of riser-to-base connections to aid in diver instruction and to test proper installation techniques.

3.3.4 Soil Testing

The coefficient of friction between the steel bottom of the gravity base and the bottom sediments is of primary interest in the design of the mooring base. This variable cannot be readibly determined from standard soils tests such as the triaxial shear test, which measures shear within the soil. Specially designed shear friction tests may be required prior to a final base design. These tests utilize sediments present at the OTEC site.

Section 4
CONCLUSIONS

Test and development programs are recommended for both the barge and spar SKSS. These programs are presented, including estimates of cost and schedule, for development, hardware and operations.

Program elements common to both systems are seafloor sampling and profiling (with the MAL requiring a more extensive area), scale model tests of the platform and SKSS, and hardware tests. MAL full scale tests include anchor assembly embedment test, and deep water handling drill for proof of deployment technique. The TAL will require special soil shear friction testing, as well as possible testing of installation techniques.

These programs will provide the data necessary to support design assumptions, validate specifications on component hardware strength and performance, and demonstrate proof of SKSS concepts, thereby contributing to the level of reliability necessary for safe stationkeeping operation over the 30 year service life.

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